

# Radio-Detection of Ultra-High-Energy Neutrinos (mostly) with ANITA

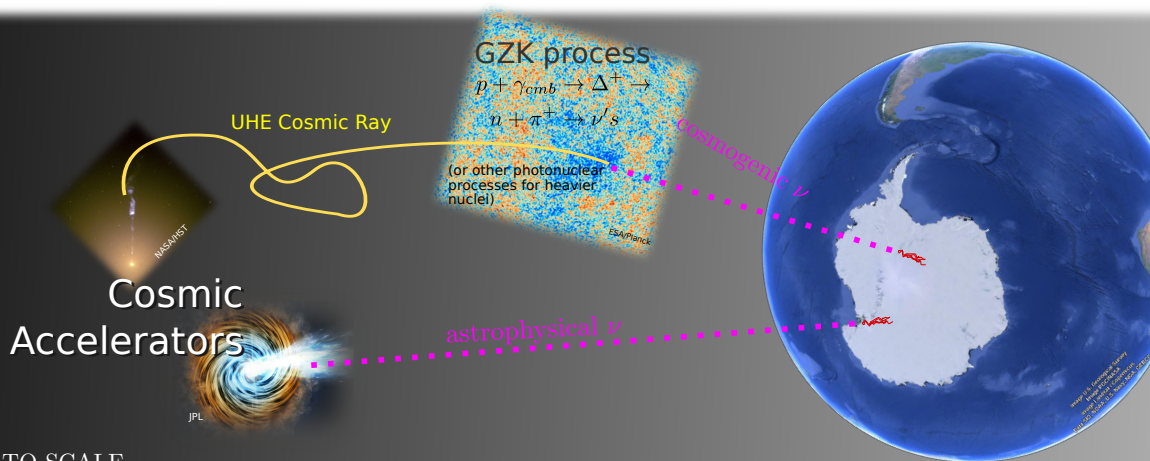


Cosmin Deaconu

University of Chicago / Kavli Institute for Cosmological Physics

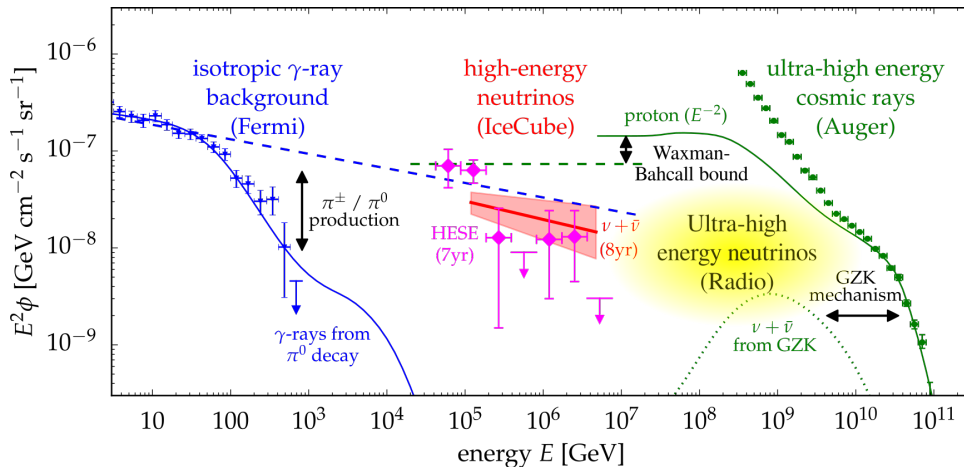
Topics in Cosmic Neutrinos Workshop  
Fermilab, October 11, 2019

# The goal of radio detection: Ultra-High-Energy $\nu$ 's ( $\gtrsim$ EeV )



NOT TO SCALE

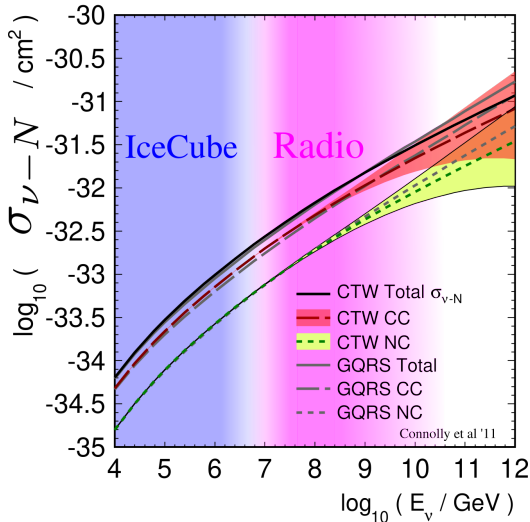
# Why? Multimessenger astrophysics!



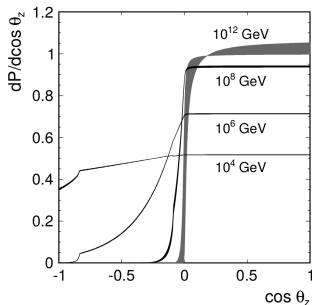
Neutrinos are ideal messengers since mostly do not interact on way here  
**Expected flux is very low, so need a big detector!**

# Why? (for particle physicists): Most energetic neutrinos we can play with!

## SM Cross-Section



- Verify Standard Model  $\nu - N$  cross-section at a new energy scale by using Earth as a filter.



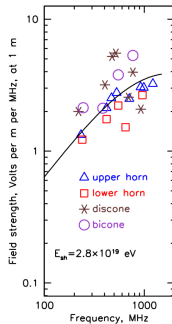
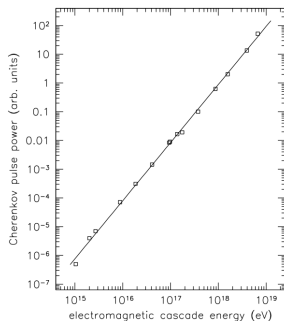
Phys. Rev. D 83, 113009

- BSM models could enhance or suppress cross-sections at high energies
- Can also probe flavor ratios, Lorentz invariance, sterile neutrinos, exotic DM, etc.



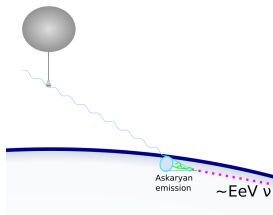
# How? Use radio emission from Askaryan effect in ice

- **Askaryan (charge-excess) radiation:** Fast-moving charge density in dielectric  $\rightarrow$  coherent emission ( $\propto E^2$ ) at long (radio) wavelengths
  - ▶ Charge excess from processes (positron annihilation; Bhabha, Moller and Compton scattering) involving electrons in material
  - ▶ At wavelengths larger than  $\mathcal{O}$ (projected lateral width), don't resolve individual charges
- Confirmed in ice with SLAC beam test (Phys.Rev.Lett.99:171101,2007).
- Radio attenuation length in ice is  $\sim 1$  km



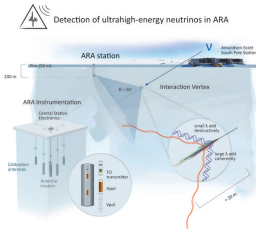
# Some ice-based Askaryan $\nu$ experiments

## ANITA\*



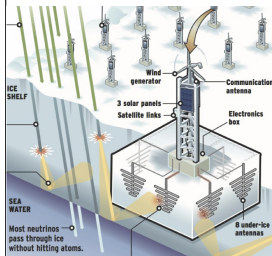
Antennas on a high-altitude balloon over Antarctica

## ARA\*



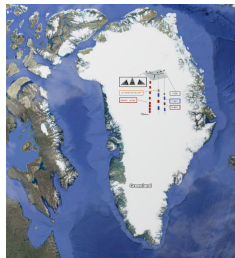
Antennas buried in ice near the South Pole

## ARIANNA



Near surface antennas on Ross Ice Shelf

## New Greenland Experiment\*

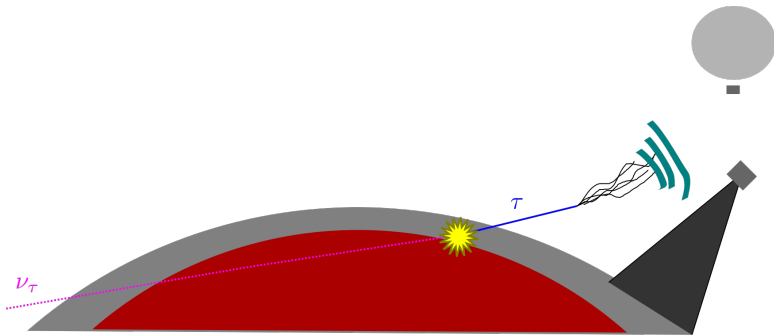


New project in Greenland!

\*denotes an experiment I work on.

## Another method: Detect upward-going showers from $\nu_\tau$

- Extensive air showers (EAS) also produce radio signal (mostly from charge-separation by Earth's magnetic field, although also an Askaryan component)
- Technique widely used to measure air showers from cosmic rays (e.g. AERA, LOFAR).
- But, a  $\nu_\tau$  interacting in the Earth can produce a  $\tau$  that escapes the Earth which can then decay in the atmosphere to produce an apparent upward-going air shower.



# Some radio experiments searching for $\nu_\tau$ channel

## ANITA\*



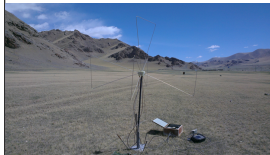
Antennas on a  
high-altitude balloon  
over Antarctica

## BEACON\*



Antenna array in  
White Mountains of  
California

## GRAND



(Eventually)  
thousands of  
antennas in the Tien  
Shan Mountains of  
China

## TAROGÉ

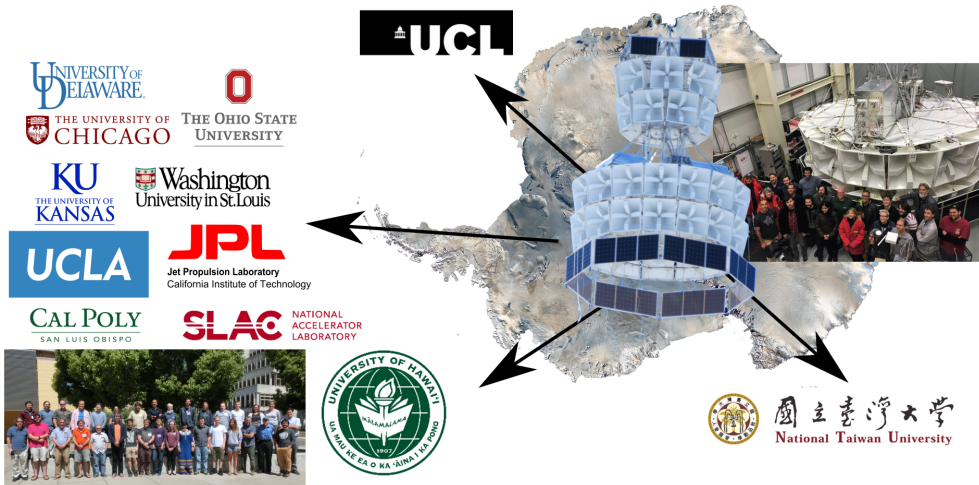


Antennas on  
mountains in  
Antarctica.

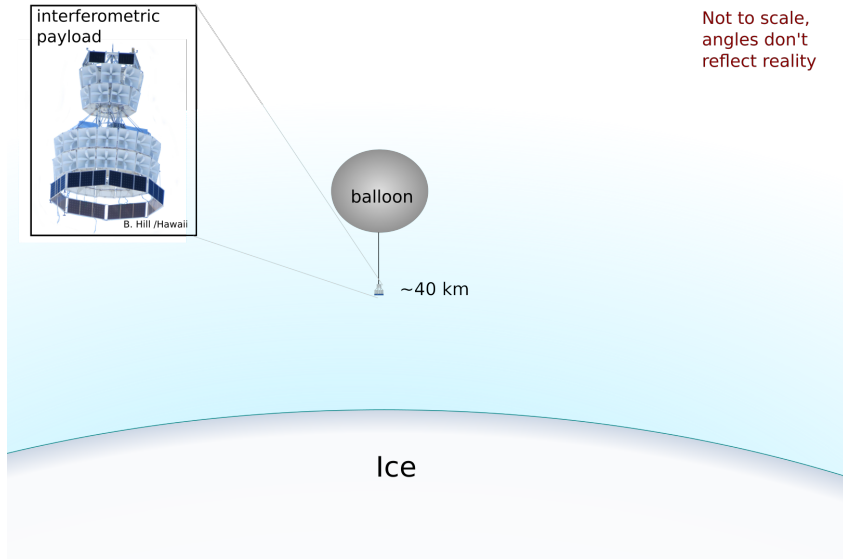
\*denotes an experiment I work on.

## ANtarctic Impulsive Transient Antenna

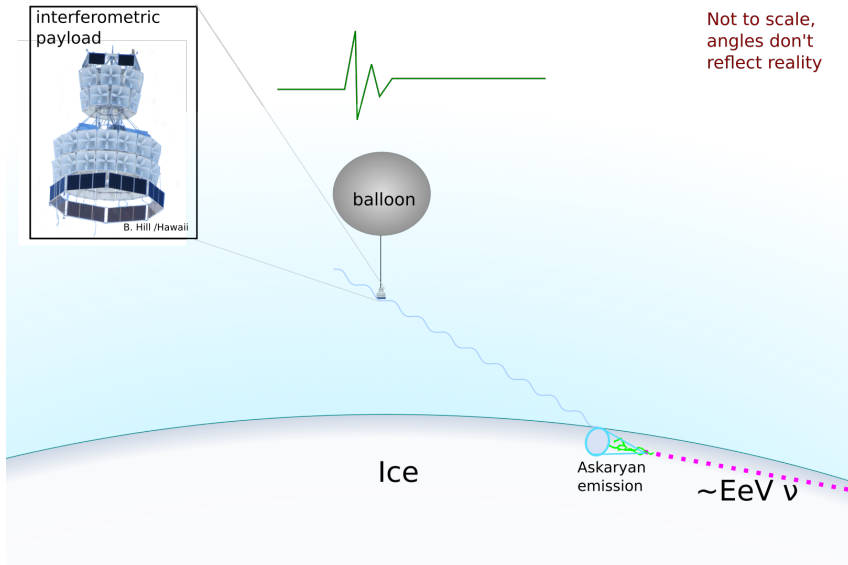
12 institutes, 3 countries, 4 continents



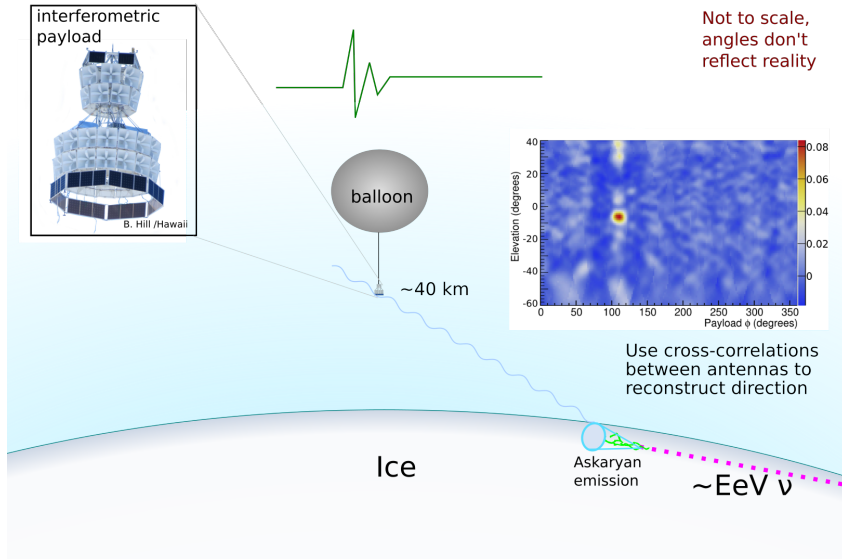
# ANITA experiment concept



# ANITA experiment concept



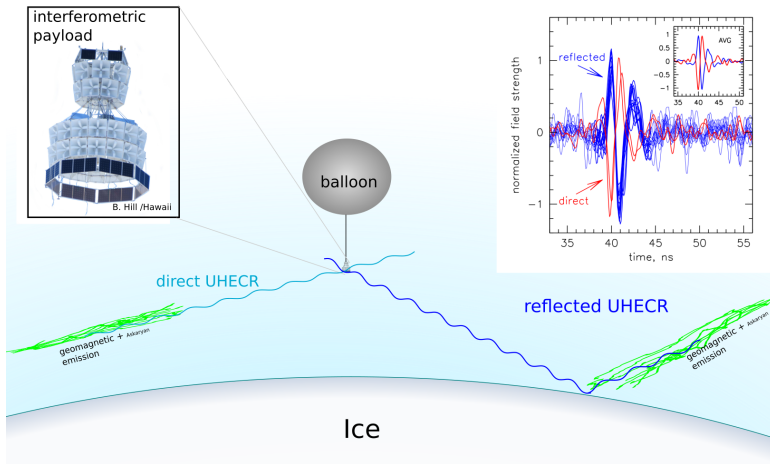
# ANITA experiment concept





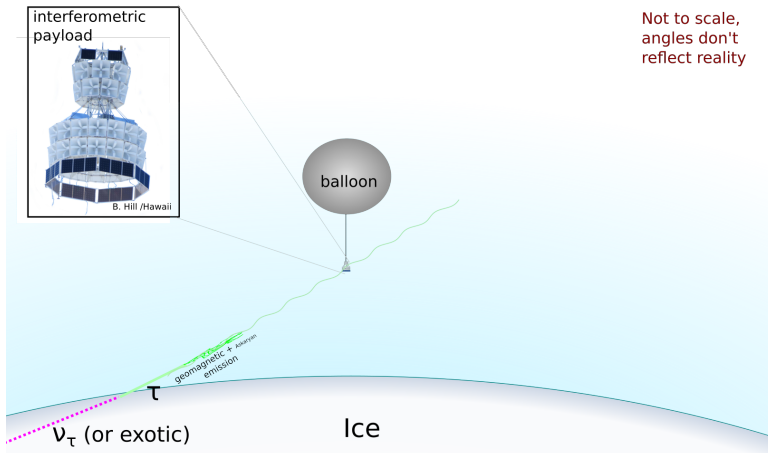
# The cosmic-ray air shower signal

- Earth's magnetic field separates charges in EASs, produces radio emission
  - ▶ “Direct”  $\sim$ horizontal CR's: miss ground.
  - ▶ “Reflected” down-going CR's: point to ground, **opposite polarity**

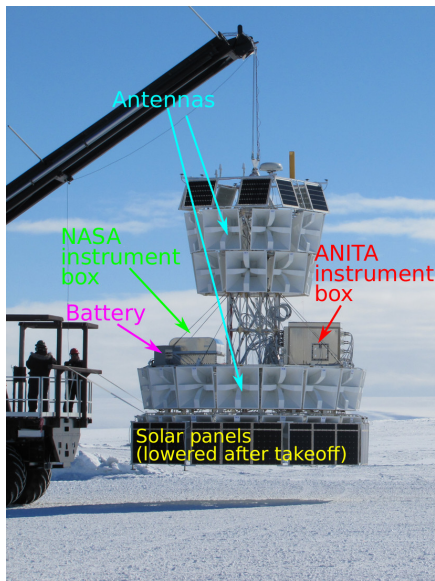


# The $\nu_\tau$ air shower signal

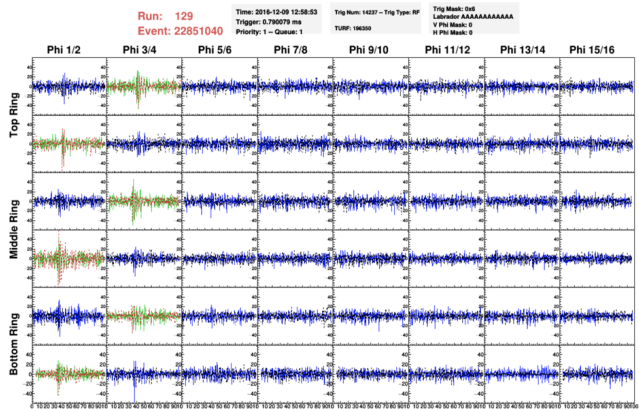
- Angle consistent with reflected UHECR, but polarity of direct
- Could be produced by a  $\nu_\tau$ -induced  $\tau$  which escapes atmosphere and decays, producing shower. Or by exotics.



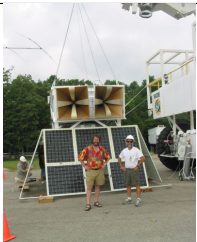
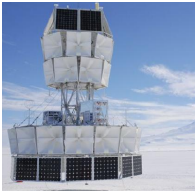

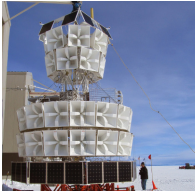

# The ANITA instrument



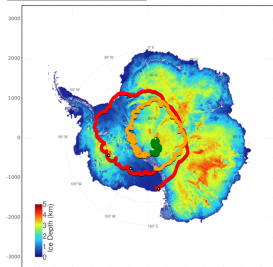
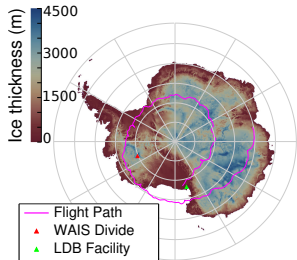
- 0.18-1.2 GHz signal split into digitizer and trigger path
  - ▶ Tunnel diode L0 trigger. combinatorics take  $\mathcal{O}(10^{5-6}$  Hz) singles rate  $\rightarrow \mathcal{O}(50$  Hz) global rate
  - ▶ Switched capacitor array digitizers,  $\sim 2.6$  GHz  $\mathcal{O}(100$  ns).



# Timeline of completed ANITA flights

ANITA-Lite	ANITA-I	ANITA-II	ANITA-III	ANITA-IV
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger

# ANITA-III (2014-2015) and ANITA-IV (2016)

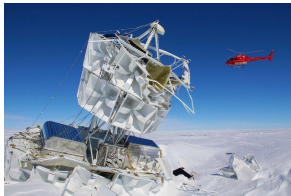


- ANITA-III:

- ▶ Independent H + V trigger
- ▶  $\sim 70$  million events recorded
- ▶ Complications from new military comm satellites  $\rightarrow$  loss of volume, significant improvements to data analysis required.

- ANITA-IV:

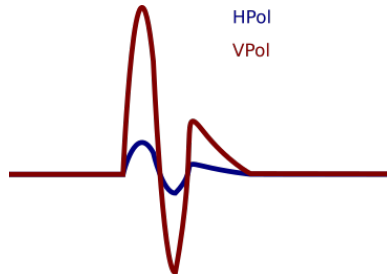
- ▶ Tunable notch filters to reduce CW, increase livetime
- ▶ New trigger uses phase shifters to convert H+V to LCP and RCP; requires coincidence of LCP and RCP, ensuring linear polarization
- ▶ Lower noise figure front-end design
- ▶  $\sim 100$  million events recorded



# Signals

## Askaryan emission from $\nu$ 's

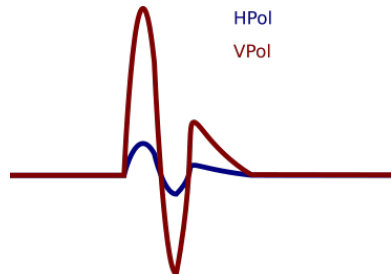
- Impulsive signal (few ns)
- Broadband
- Linearly polarized; mostly vertically-polarized (VPol) due to interaction geometry (Earth opaque to EeV  $\nu$ 's) and transmission through air-ice boundary (Fresnel coefficients).



# Signals

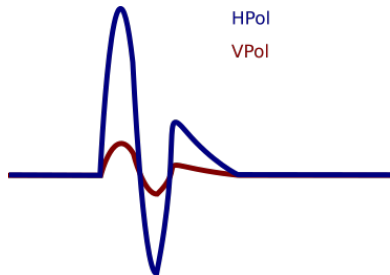
## Askaryan emission from $\nu$ 's

- Impulsive signal (few ns)
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## Geomagnetic emission from EAS

- Impulsive signal
- More low-frequency weighted
- Linearly polarized; due to Earth's magnetic field, primary horizontally-polarized (HPol)



# Signals and backgrounds (fake $\nu$ s)

## Askaryan emission from $\nu$ 's

- Impulsive signal (few ns)
- Broadband
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## Geomagnetic emission from EAS

- Impulsive signal
- More low-frequency weighted
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## Continuous wave (CW) signals

Anthropogenic narrow-band signals (from satellites and bases) contaminate most data so must be filtered.

## RFI from payload ("payload blasts")

Timing between antennas not plane wave-y.

## Thermal noise

Incoherent random noise, that sometimes by chance looks impulsive (but not correlated between antennas).

## Impulsive anthropogenic emission

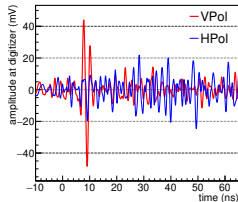
Transformers, engines, etc. produce broadband impulsive emission that can mimic  $\nu$ 's. Use spatial clustering of events passing first-round cuts to remove. **Dominant background.**



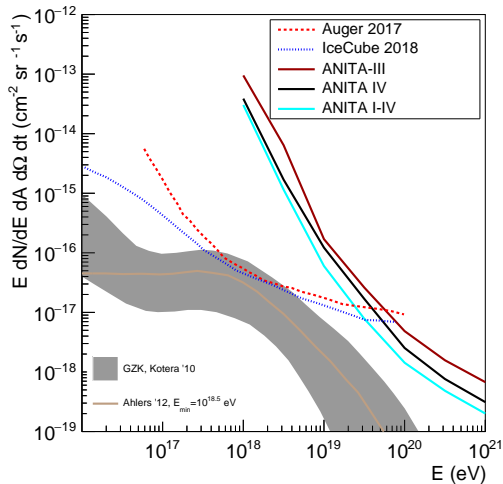
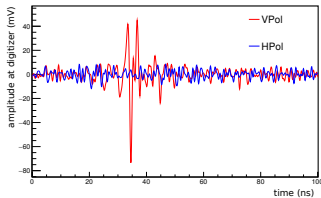
# Diffuse askaryan $\nu$ results

- ANITA-III: (Phys.Rev. D98 (2018) no.2, 022001)  
Most sensitive search found one candidate on a background of  $0.7^{+0.5}_{-0.3}$  events.
- ANITA-IV: (Phys.Rev. D99 (2019) no.12, 122001)  
Most sensitive search found one candidate on a background of  $0.64^{+0.69}_{-0.45}$  events.

ANITA-III candidate:



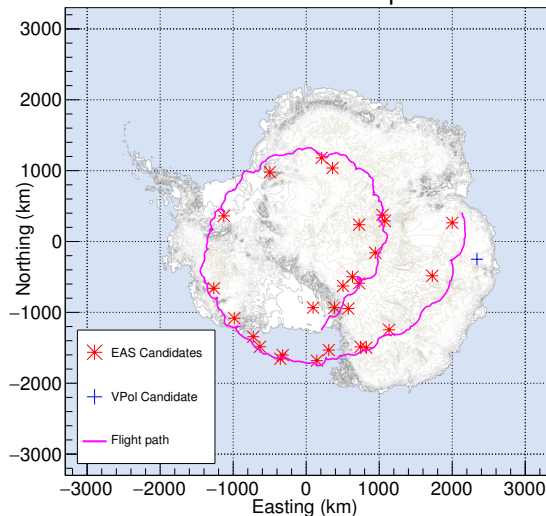
ANITA-IV candidate:



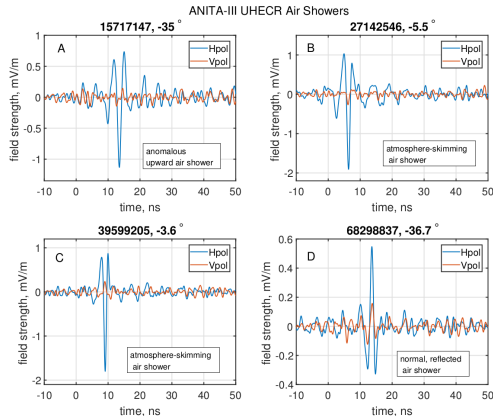
# Air shower searches

- Due to potential for upgoing showers, searches performed blind to polarity.
- To be an air shower candidate, in addition to being isolated, impulsive and primarily HPol, must:
  - ▶ Match expected air shower shape (which we know, since we've detected EAS before)
  - ▶ Have polarization angle consistent with local magnetic field
- $\mathcal{O}(20\text{-}30)$  EAS candidates identified in each of ANITA-III and ANITA-IV.

ANITA-III event map:



# Upward shower searches



Top-Left: Anomalous ANITA-III event

Top-Right, Bottom-Left: Direct UHECR candidates

Bottom-Right: A reflected UHECR candidate

- An anomalous event found in ANITA-III (Phys.Rev.Lett. 121 (2018) no.16, 161102), similar to event found in ANITA-I.
- Mostly HPol, matches UHECR template, polarity consistent with direct cosmic ray event, but clearly points to ice, so consistent with an upward going air shower.
- “Looks like” a  $\nu_\tau \rightarrow \tau$  candidate, but chord length through Earth in tension with SM cross-section and flux in tension with Auger and IceCube limits; a number of other explanations have been proposed.

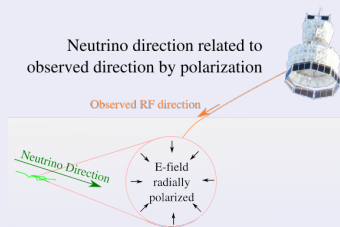
# Ongoing ANITA searches

## ANITA-IV upward air shower search (i.e. polarity unblinding)

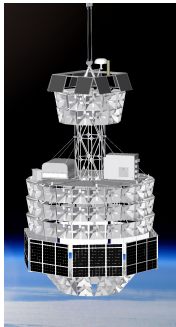
- Holdup is calibration of impulse response, which is more complicated in ANITA-IV due to the programmable notch filters and changes to frontend design.
- Because different filter configurations during flight, must take responses into account when comparing polarity! Lots of work on deconvolution.

## Searches for neutrinos in coincidence with sources ongoing in ANITA-III and ANITA-IV

- Consider e.g. putative IceCube sources, flaring blazars, and GRB's
- By constraining time and direction, lower backgrounds and analysis threshold
- Using polarization information, simulations preliminarily indicate RA and dec resolution of a few degrees.
- Intriguingly, the IceCube “neutrino burst” from TXS 0506+056 occurred during ANITA-III flight



# Future of ANITA: Payload for Ultrahigh Energy Observations (PUEO)



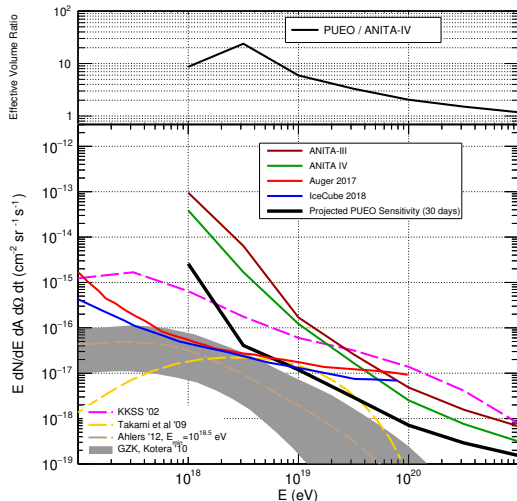
PUEO



*pueo*

- Additional antennas (120 instead of 48), but with a higher cutoff frequency (300 vs. 180 MHz).
- Beamforming trigger using few-bit streaming digitizers to lower trigger threshold
- 24 antennas canted down to fill gap in ANITA elevation coverage (and further investigate steep air shower events)
- Improved digitizers with better response at high frequencies
- Up to 10X more sensitive than ANITA-IV

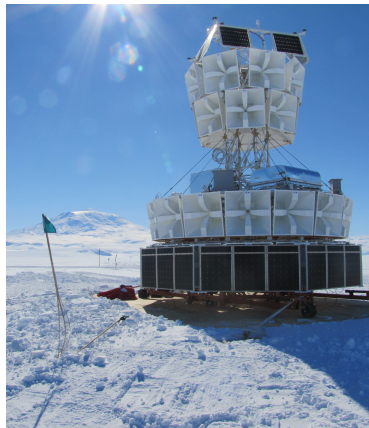
## Projected PUEO sensitivity:



# Conclusions

- Radio detectors can be used to search for ultra-high energy neutrinos.
- ANITA I-IV combined set the best limits on UHE  $\nu$  flux above  $10^{19.5}$  eV.
- Many EASs detected in ANITA-III and ANITA-IV.
- One of the ANITA-III EAS has anomalous polarity, consistent with an upward-going air shower.
- Stay tuned for ANITA-IV polarity unblinding and ANITA-III and ANITA-IV source searches!
- The proposed PUEO will have substantial hardware and sensitivity improvements.

Thank You!



Questions?

# Backup Slides

# (Some) upward shower explanations

## $\nu_\tau$ -induced EAS

- + Would produce upward-going EAS
- Chord through Earth not compatible with SM cross-section
- Tension with IceCube and Auger results

## Funny reflection of UHECR EAS

- + Apparent upward-going EAS shower
- Hard to invert polarity but maintain coherence
- Would likely have seen effect in data from HiCal (trailing balloon with HV pulser)

## Anthropogenic Background

- + No physics to explain
- We consider it unlikely

## Transition Radiation from UHECR EAS

- + Could produce impulsive emission with right polarization
- Work needed to see if can mimic signal

## Exotics (e.g. heavy $\nu$ DM, sterile $\nu$ )

- + Could produce upward-going EAS
- New physics
- Tension with IceCube and Auger

## Not geomagnetic, instead Askaryan

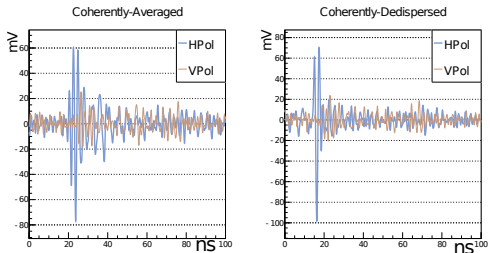
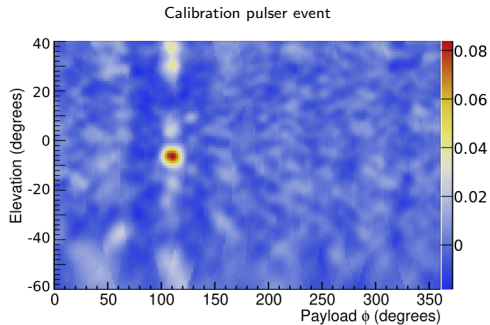
- + Could produce impulsive emission
- + Not in tension with other experiments
- If from  $\nu$ , observed polarization unlikely
- If from some exotic, need new physics.



# Sketch of analysis

Three independent blind  $\nu$  analyses for ANITA-III, two for ANITA-IV. Basic flow:

- 1 Filter waveforms (reduce CW) and remove events failing quality cuts
- 2 Form correlation map, where we calculate channel cross-correlations with different direction assumptions
- 3 From peaks of correlation map, form coherent waveforms, generate features (e.g. impulsivity, linear polarization fraction) used to cut out thermal noise
- 4 Use pointing information to point to continent; select regions with little anthropogenic activity.



# The Raw Data (a Calibration Pulse, Not a $\nu$ )

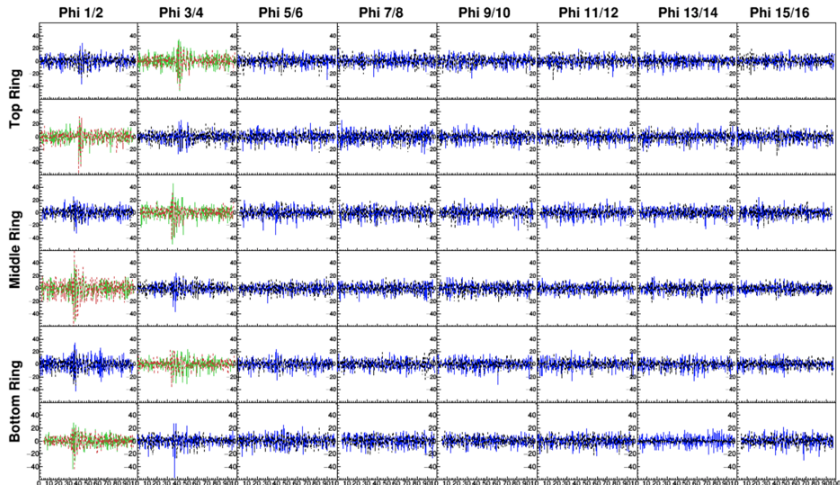
Run: 129  
Event: 22851040

Time: 2016-12-09 12:58:53  
Trigger: 0.790079 ms  
Priority: 1 -- Queue: 1

Trig Num: 14237 -- Trig Type: RF  
TURF: 196350

Trig Mask: 0x6  
Labrador AAAAAAAAAA  
V Phi Mask: 0  
H Phi Mask: 0

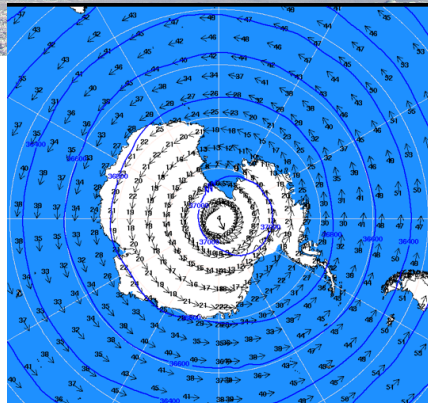
- 48 dual-polarization horn antennas
- Sampled at  $\approx 2.6$  GHz's
- 100 ns per event
- 50 Hz global trigger rate
- $\mathcal{O}(10^7)$  RF triggers per flight (ANITA-III and IV)



# Ballooning in Antarctica

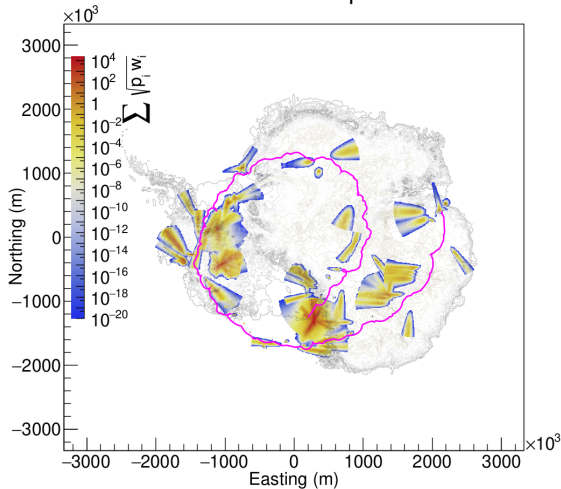


- Antarctica not only has abundant ice but also hosts the NASA long duration balloon program!
- At float (35-40 km), balloon expands to size of football stadium.



# Using Spatial Information to Remove Anthropogenics

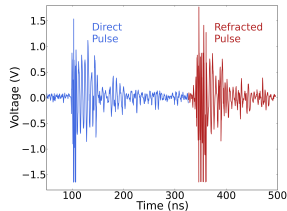
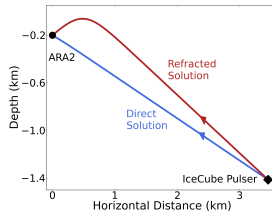
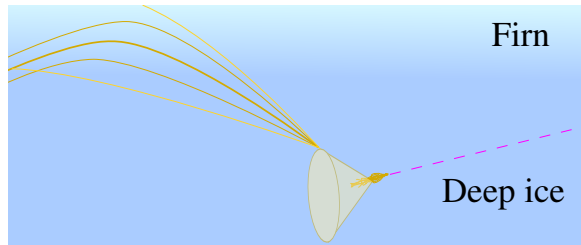
Source Map



- We assume anthropogenic emission is spatially clustered on the continent, so we only consider isolated events as candidates.
- For each signal-like event, we measure a direction with some pointing resolution.
- One example clustering algorithm:
  - ▶ Project all interesting events to continent and accumulate to form a “clustering map.” Use to compute overlap integral of each event with all other events.
  - ▶ Isolated events will have overlap integrals close to zero
- Other methods to tackle anthropogenics include pairwise event clustering or a binned continent analysis.

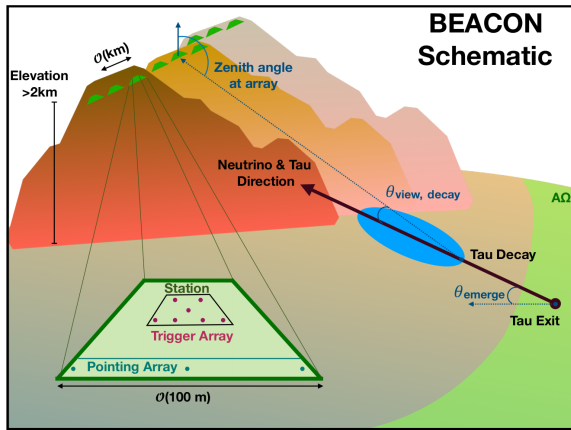
# Ice considerations: Surface vs. deep antennas

- Near-surface antennas are easier to deploy, and more flexible (can use higher gain antennas, same antenna for all polarizations.)
- But top layer of ice (“firn”) has density gradient  $\rightarrow$  index of refraction gradient so not all signals reach surface
- Deep antennas see more volume, but drilling adds to cost and antenna options limited by borehole size
- Another consequence of firn is existence of with multiple paths (“direct” and “refracted”) which allow for more precise vertexing

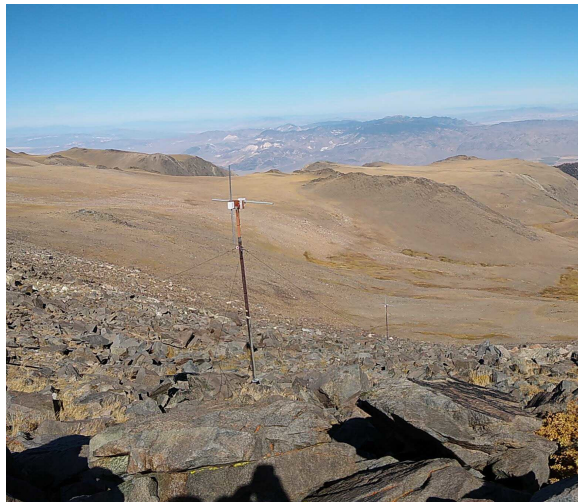


# BEACON concept

- Phased array trigger on top of a mountain
- Current prototype running in White Mountains of California



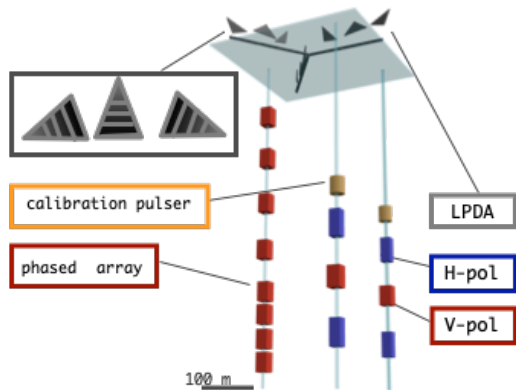
S. Wissel



New antennas deployed a week ago!

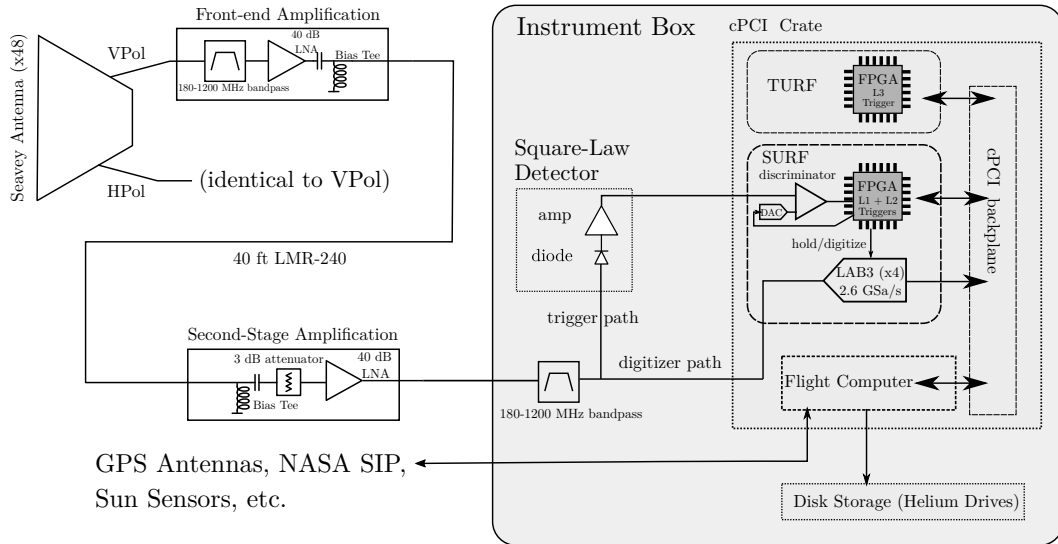
# New Greenland Experiment

- Constructing a new radio neutrino array near Summit Station Greenland
- Preliminary design includes 100m deep phased antenna array and surface antennas for CR veto and enhanced reconstruction
- Deploying as soon as 2020!



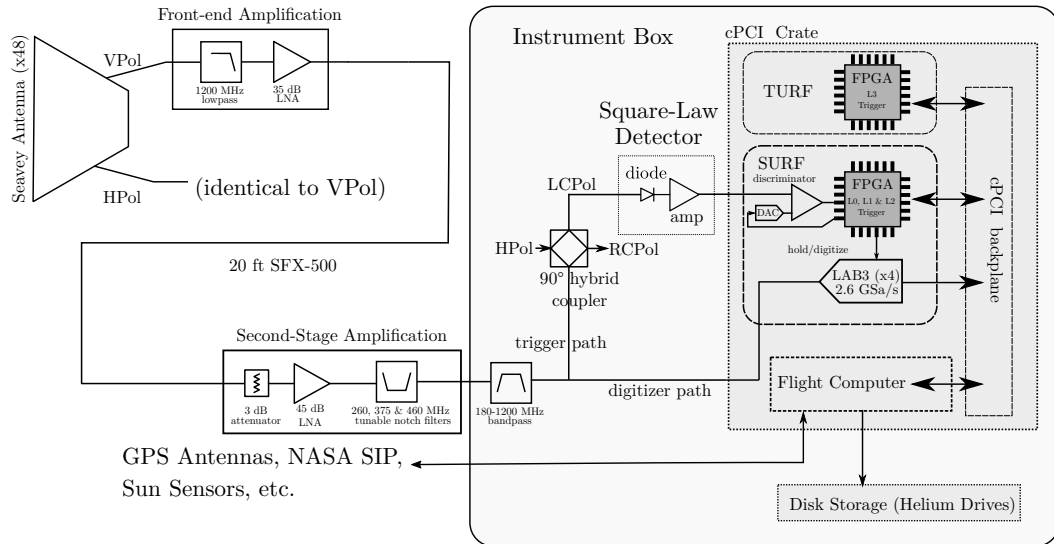
A. Nelles

# ANITA-III Block Diagram

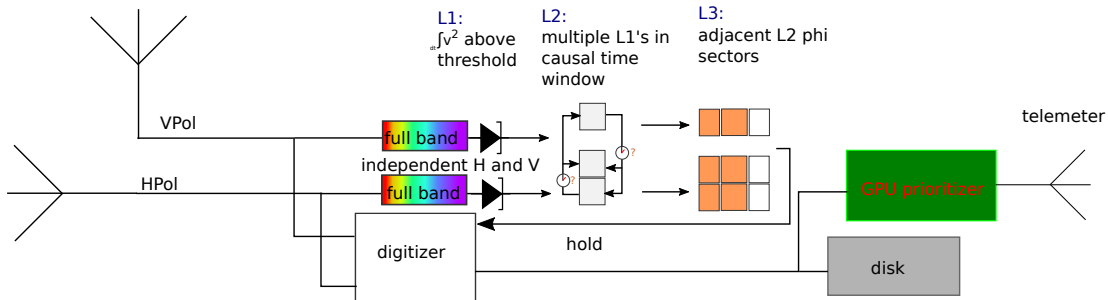




# ANITA-IV Block Diagram



# ANITA-III Trigger



# ANITA-IV Trigger

